

WZ Cygni: a Marginal Contact Binary in a Triple System?

Jae Woo Lee, Seung-Lee Kim, Chung-Uk Lee, Ho-Il Kim, Jang-Ho Park, and Tobias Cornelius
Hinse

Korea Astronomy and Space Science Institute, Daejeon 305-348, Korea

jwlee@kasi.re.kr, slkim@kasi.re.kr, leecu@kasi.re.kr, hikim@kasi.re.kr,
pooh107162@kasi.re.kr, tobiash@kasi.re.kr

ABSTRACT

We present new multiband CCD photometry for WZ Cyg made on 22 nights in two observing seasons of 2007 and 2008. Our light-curve synthesis indicates that the system is in poor thermal contact with a fill-out factor of 4.8 % and a temperature difference of 1447 K. Including our 40 timing measurements, a total of 371 times of minimum light spanning more than 112 yr were used for a period study. Detailed analysis of the $O-C$ diagram showed that the orbital period has varied by a combination with an upward parabola and a sinusoid. The upward parabola means the continuous period increase and indicates that some stellar masses are thermally transferred from the less to the more massive primary star at a rate of about $5.80 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$. The sinusoidal variation with a period of 47.9 yr and a semi-amplitude of 0.008 d can be interpreted most likely as the light-travel-time effect due to the existence of a low-mass M-type tertiary companion with a projected mass of $M_3 \sin i_3 = 0.26 M_{\odot}$. We examined the evolutionary status of WZ Cyg from the absolute dimensions of the eclipsing pair. It belongs to the marginal contact binary systems before broken-contact phase, consisting of a massive primary star with spectral type of F4 and a secondary with the type K1.

Subject headings: binaries: close — binaries: eclipsing — stars: individual (WZ Cygni)

1. INTRODUCTION

According to the thermal relaxation oscillation (TRO) theory (Lucy 1976; Lucy & Wilson 1979), contact binaries oscillate between contact and non-contact states on the thermal time-scales ($\sim 10^7$ yr) because of non-thermal equilibrium. The systems in good thermal contact show typical W UMa-type light curves with nearly equal eclipse depths, while those in broken-contact state display significant temperature differences between the binary components and minima of unequal depth. Such oscillations are normally accompanied by a thermal mass transfer between both components, and hence cause observable period changes. In a state evolving from contact to non-contact phases, mass moves from the less massive component toward the more massive star, which is opposite to

the energy flow, and an orbital period increase occurs. Since the direction of mass transfer can be directly inferred from the observed period change, orbital period studies may provide a significant clue to understand the structure and evolutionary state of this kind of system. Such examples are the short-period binaries CN And (van Hamme et al. 2001; Lee & Lee 2006) and V432 Per (Lee et al. 2008b; Odell et al. 2009), which showed the secular period decrease and increase, in the same order, caused by mass transfer. The former is a semi-detached system with the more massive star filling its limiting lobe and the less massive star very close to lobe-filling, and the latter is a detached system in which both components almost fill their inner Roche lobe. The period changes and Roche configurations indicate the two systems may be in a broken or marginal contact stage within parameter uncertainties.

WZ Cyg (BD + 38°4262, 2MASS J20530677+3849406; F4 V) was announced as an eclipsing binary with a short orbital period of 0.5845 d (cf. Shapley 1913) and has been studied by several investigators. Shaw (1994) classified the system as a near-contact binary (hereafter NCB) whose subclass is unknown. Rovithis et al. (1999) published the first photoelectric light curves and analyzed these. They suggested that the binary star is a contact system of β Lyr-type with a photometric mass ratio of $q=0.54$. Most recently, Siwak et al. (2010) computed the binary parameters from their CCD observations and the unpublished radial-velocity curves obtained by Waldemar Ogloza and Slavek M. Rucinski at the David Dunlap Observatory. The results indicate that WZ Cyg has a near-contact configuration with a mass ratio of $q=0.63$, an orbital inclination of $i=83^\circ.50$, and a temperature difference of $\Delta T=1598$ K between the components.

A period study of the system was carried out by Rovithis et al. (1996, 1999), who reported that the orbital period has been increasing. Up to now, eclipse timings have been obtained assiduously by numerous observers and the observation history is long enough to investigate the orbital period change. In this paper, we present and analyze new multiband light curves and suggest that WZ Cyg is a marginal contact binary in a triple system.

2. CCD PHOTOMETRIC OBSERVATIONS

New photometry of WZ Cyg was performed on 22 nights from 2007 October 26 through 2008 October 20 in order to obtain multicolor light curves and to look for possible flare-like phenomena. The observations were taken with a SiTe 2K CCD camera and a *BVRI* filter set attached to the 61-cm reflector at Sobaeksan Optical Astronomy Observatory (SOAO) in Korea. The instrument and reduction method are the same as those described by Lee et al. (2007). Since an image field-of-view (FOV) was large enough to observe a few tens of nearby stars simultaneously, we monitored them along with the program target. As in the method described by Lee et al. (2010), we made an artificial reference source from several stars on the CCD frame and examined candidate comparison stars. Among a few possible candidates, we chose TYC 3167-2078-1 (2MASS J20524841+3850375; $V_T=+11.04$, $(B - V)_T=+0.57$) as an optimal comparison star.

A total of 3194 individual observations was obtained in the four bandpasses (812 in B , 799 in V , 791 in R , and 792 in I) and a sample of them is listed in Table 1. The natural-system light curves of WZ Cyg are plotted in the upper panel of Figure 1 as differential magnitudes *versus* orbital phases, where the open circles and plus symbols are the individual measures of the 2007 and 2008 seasons, respectively. The differences ('07–'08) between the two seasons are plotted in the lower panel. Although we show no figure illustrating variability of the color indices, their phase-locked variations are large and in the expected senses.

In addition to these complete light curves, four primary eclipse timings were obtained in both 2009 and 2010 with the same telescope and filters but, replacing the SITE 2K CCD camera, with an electronically cooled FLI IMG4301E CCD camera. The new CCD chip has 2084×2084 pixels, a pixel size of $24 \mu\text{m}$, and the FOV of about $20'.9 \times 20'.9$. TYC 3167-1967-1 also served as the comparison star.

3. LIGHT-CURVE SYNTHESIS AND ABSOLUTE DIMENSIONS

Our observations for WZ Cyg show a typical light curve of a β Lyr-type eclipsing binary (Rovithis et al. 1999; Siwak et al. 2010). Rovithis et al. (1999) reported three flashes made on the 28-29th of June 1993 and suggested that these are related to a magnetic activity on the secondary component. However, the other datasets (their observations in 1994, Siwak et al. 2010, our data) did not indicate any peculiar light variations. As shown in the bottom panel of Figure 1, mean brightness differences between the 2007 and 2008 seasons are smaller than the observational error of ± 0.01 mag: -0.005 ± 0.020 mag for B , -0.002 ± 0.019 mag for V , $+0.003 \pm 0.021$ mag for R , and -0.002 ± 0.022 mag for I , respectively. The SOAO observations did not display the year-to-year light variability above the photometric limit.

In order to derive the binary parameters of the system, we analyzed simultaneously our $BVRI$ light curves in a manner similar to that for the near-contact binaries RU UMi (Lee et al. 2008a) and GW Gem (Lee et al. 2009) by using the 2003 version of the Wilson-Devinney synthesis code (Wilson & Devinney 1971). The surface temperature of the hotter, more massive primary star was assumed to be $T_1=6530$ K, according to its spectral type F4 V given by Siwak et al. (2010). The gravity-darkening exponents and the bolometric albedos were initialized at standard values ($g=0.32$ and $A=0.5$) for stars with convective envelopes. The logarithmic bolometric (X, Y) and monochromatic (x, y) limb-darkening coefficients were interpolated from the values of van Hamme (1993) and were used in concert with the model atmosphere option.

Our light-curve synthesis has been carried out in two stages. In the first stage, all SOAO observations were examined for various modes (i.e., Roche configurations) of the binary code and for a series of models with the mass ratios in step of 0.02 between 0.4 and 1.0, so as to understand the geometrical structure of the system and to confirm a spectroscopic mass ratio of $q=0.631 \pm 0.036$ (Siwak et al. 2010). Furthermore, a third light source (ℓ_3) was considered throughout the analyses.

This procedure showed acceptable photometric solutions only for contact mode 3 and indicated a somewhat broad range of $0.56 \leq q \leq 0.64$, where the fill-out factor decreases toward larger mass ratios from 8 % at $q=0.56$ to 5 % at $q=0.64$. But, the trials for a possible ℓ_3 failed to achieve convergence.

In the second stage, the previously determined parameters and the mass ratio from Siwak et al. (2010) were used as the initial values. Considering its effective temperature with an accuracy no better than 100~200 K, the envelopes of the primary star should lie close to the lower limit between the radiative and convective atmospheres, so A_1 and g_1 were included as additional free variables. Final results are given in Table 2 together with those of Siwak et al. (2010) for comparison and plotted in Figure 2, where, for clarity, individual observations have been compiled into 100 mean points using bin widths of 0.01 in phase for each filtered light curve. As seen in the figure, the computed light curves describe the SOAO multiband data quite well.

Our result represents the system as a contact binary with a fill-out factor of 4.8 % and with a considerably large temperature difference of 1447 K. This implies that both component stars are marginally over-contact with respect to the inner Roche lobe and the thermal contact between them is poor. But contrarily, Siwak et al. (2010) reported WZ Cyg to be a NCB in which the two components are at or near their lobes. From our binary parameters and the spectroscopic orbit of Siwak et al. (2010), we obtained the absolute dimensions for the system listed in Table 3, assuming that the temperature of each component has an error of 200 K and that the bolometric magnitude of the Sun is $M_{\text{bol}\odot}=+4.73$. For the absolute visual magnitudes (M_V), we used the bolometric corrections (BCs) from the scaling between $\log T$ and BC recalculated by Torres (2010) from Flower’s (1996) table.

4. ORBITAL PERIOD STUDY

We determined 15 times of minimum light with the weighted means for the timings in each filter by using the method of Kwee & van Woerden (1956). Twenty-five additional timings were derived by us using the data from the WASP (Wide Angle Search for Planets) public archive (Butters et al. 2010). From the database of Kreiner et al. (2001) and from more recent literature, 331 timings (33 photographic plate, 213 visual, 35 photographic, 11 photoelectric, and 39 CCD) have been added to our measurements. Our period study is based on a total of 371 times of minimum light spanning more than 112 years. All photoelectric and CCD timings are listed in Table 4, wherein the second and third columns give the HJED (Heliocentric Julian Ephemeris Date) timings transformed to the terrestrial time scale (Bastian 2000) and their uncertainties, respectively. Because almost all but the CCD timings were published without error information, the following standard deviations were assigned to the timing residuals based on observational method for the period analysis of WZ Cyg: ± 0.0165 d for photographic plate, ± 0.0067 d for visual, ± 0.0048 d for photographic, and ± 0.0029 d for photoelectric minima. Relative weights were then calculated as the inverse squares of these values consistent with the errors.

As suggested by Rovithis et al. (1996, 1999), we examined whether the orbital period could be represented by a quadratic ephemeris via a continuous period increase but failed to give a satisfactory result. Instead, we found that all times of minimum light are best fitted by the combination of an upward parabolic variation and a light-travel time (LTT) effect caused by the presence of a third body in the system, namely a quadratic *plus* LTT ephemeris:

$$C = T_0 + PE + AE^2 + \tau_3,$$

where τ_3 is the LTT due to a third body (Irwin 1952, 1959) and introduces additional five parameters ($a_{12} \sin i_3$, e , ω , n , T). Here, $a_{12} \sin i_3$, e , and ω are the orbital parameters of the eclipsing pair around the mass center of the triple system. The parameters n and T denote Keplerian mean motion of the mass center of the eclipsing pair and the epoch of its periastron passage, respectively. The Levenberg-Marquart algorithm (Press et al. 1992) was applied to solve for the unknown parameters of the ephemeris. The results are summarized in Table 5, together with the third-body masses (M_3) calculated for three different inclinations of i_3 . Our absolute dimensions have been used for these and subsequent calculations.

The $O-C$ diagram constructed with the linear terms of the equation is plotted in the top panel of Figure 3, where the continuous curve and the dashed parabola represent the full contribution and the quadratic term, respectively. The middle panel displays the LTT orbit, and the bottom panel the residuals from the complete ephemeris. These appear as $O-C_{\text{full}}$ in the fifth column of Table 4. As displayed in Figure 3, the quadratic *plus* LTT ephemeris currently provides a good representation of all the $O-C$ residuals. If the third companion is on the main sequence and its orbit is coplanar with the eclipsing binary (i.e., $i_3=83^\circ.2$), the mass of the object is $M_3=0.26 M_\odot$ and its radius and temperature are calculated to be $R_3=0.27 R_\odot$ and $T_3=3048 \text{ K}$, respectively, using the mass-radius and mass-temperature relations from well-studied eclipsing binaries (Southworth 2009). These correspond to a spectral type of about M6 V and a bolometric luminosity of $L_3=0.006 L_\odot$ and contribute about 0.1% to the total light of the triple system. So, it will be difficult to detect such a companion from the light-curve analysis and spectroscopic observations.

The positive coefficient of the quadratic term in Table 5 indicates a continuous period increase with a rate of $3.78 \times 10^{-8} \text{ d yr}^{-1}$, which can be explained by a mass transfer from the cool secondary star to its more massive primary component because WZ Cyg is a contact binary system. Under the assumption of conservative mass transfer, the transfer rate is $5.80 \times 10^{-8} M_\odot \text{ yr}^{-1}$. If the secondary star transfers its present mass to the primary component on a thermal time scale $\tau_{\text{th}}=(GM_2^2)/(R_2L_2)$, then $\tau_{\text{th}} = 1.95 \times 10^7 \text{ yr}$ and mass is transferred to the primary at a rate given roughly by $M_2/\tau_{\text{th}}=5.12 \times 10^{-8} M_\odot \text{ yr}^{-1}$. This value is very close to the mass transfer rate calculated from our quadratic term, which means that the mass transfer between the two stars can explain the secular period increase of the system satisfactorily.

5. DISCUSSION

The periodic oscillation in the $O-C$ residuals could be caused by a magnetic activity cycle in the late-type star, as was initially proposed by Applegate (1992) and later modified by Lanza et al. (1998). With the periods (P_3) and amplitudes (K) listed in Table 5, the model parameters were calculated from the Applegate formulae and are listed in Table 6, where the rms luminosity changes (Δm_{rms}) converted to magnitude scale were obtained with equation (4) in the paper of Kim et al. (1997). In the table, the variations of the gravitational quadrupole moment (ΔQ) are two orders of magnitude smaller than typical values of $10^{51} \sim 10^{52}$ for close binaries (Lanza & Rodono 1999). A recent study by Lanza (2006) indicates that the Applegate mechanism is not adequate to explain the orbital period modulation of close binary systems with a late-type secondary. Moreover, it is difficult for the model to produce perfectly smooth and tilted periodic component in the $O-C$ variation. Therefore, the cyclical variation most likely arises from the LTT effect due to the existence of an unseen third companion star gravitationally bound to the eclipsing pair WZ Cyg.

Our absolute parameters of WZ Cyg are used to study the evolutionary status of the binary system in the mass-radius and mass-luminosity diagrams given by Hilditch et al. (1988). In these diagrams, the primary star lies in the main-sequence band between the zero-age main sequence and the terminal-age main sequence (TAMS), while the secondary is slightly beyond TAMS, implying that the component is larger and brighter than expected for its mass. The binary system is closer to the general pattern of contact binaries, rather than to that of NCBs. Nonetheless, the location of the secondary in the Hertzsprung-Russell diagram appears to be among NCBs, which significantly depends upon the adopted effective temperatures. Considering a period increase driven by mass transfer from the secondary to the primary component, WZ Cyg may be in a marginal contact stage evolving from contact to non-contact phases as it undergoes TRO.

The tertiary component in WZ Cyg may have played an important role in the formation of an initial tidal-locked detached progenitor of the eclipsing binary by transferring angular momentum via Kozai oscillation (Kozai 1962; Pribulla & Rucinski 2006) or a combination of the Kozai cycle and tidal friction (Fabrycky & Tremaine 2007). This would cause WZ Cyg to evolve into present configuration by angular momentum loss through magnetic braking and ultimately to coalesce into single stars. The existence of the third body is consistent with the suggestion of Pribulla & Rucinski (2006) that most contact binaries exist in multiple systems. Future high-precision long-term observations are needed to verify our results for the orbital behavior and the evolutionary status of the system.

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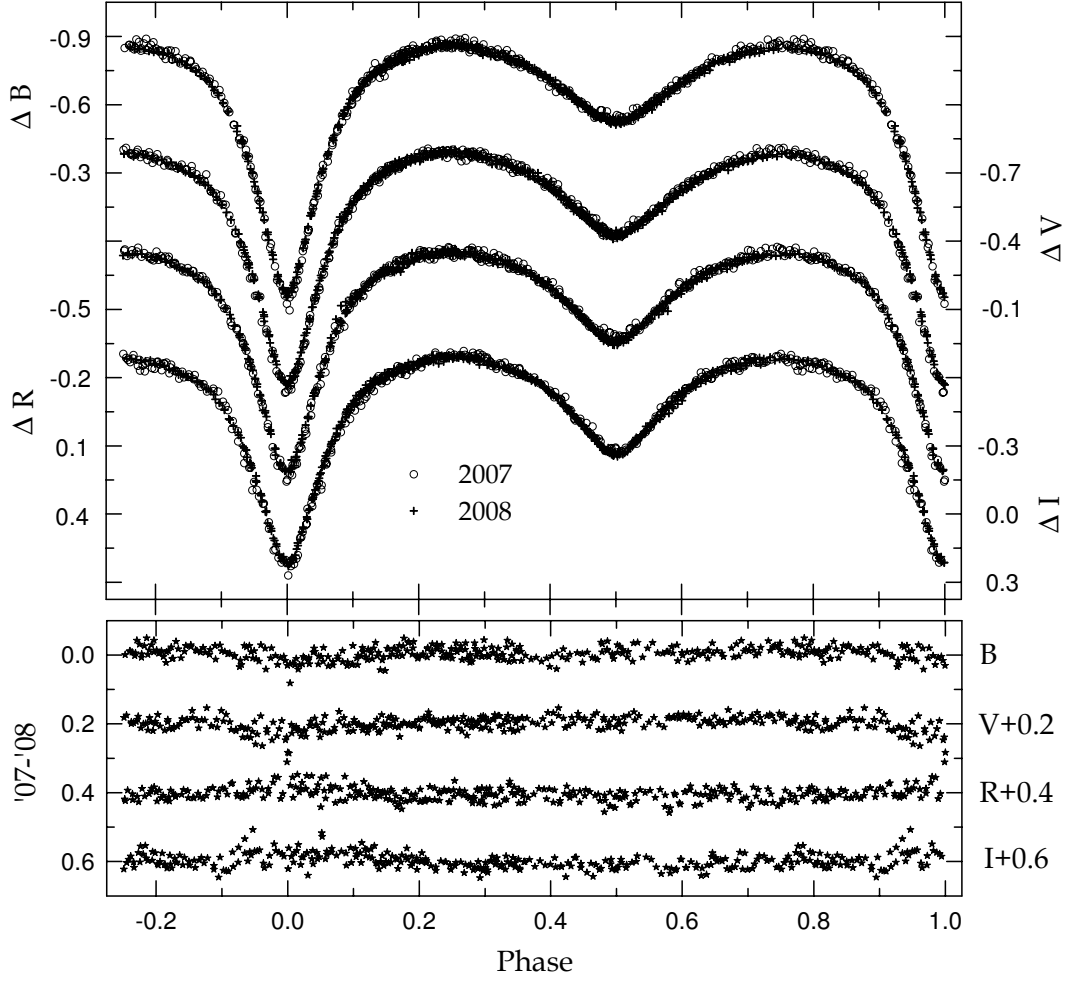


Fig. 1.— The top panel displays our light curves of WZ Cyg in the B , V , R , and I bandpasses. Because of the high density of the points, many of the 2007 measures cannot be seen individually. The differences between the two seasons are shown in the bottom panel.

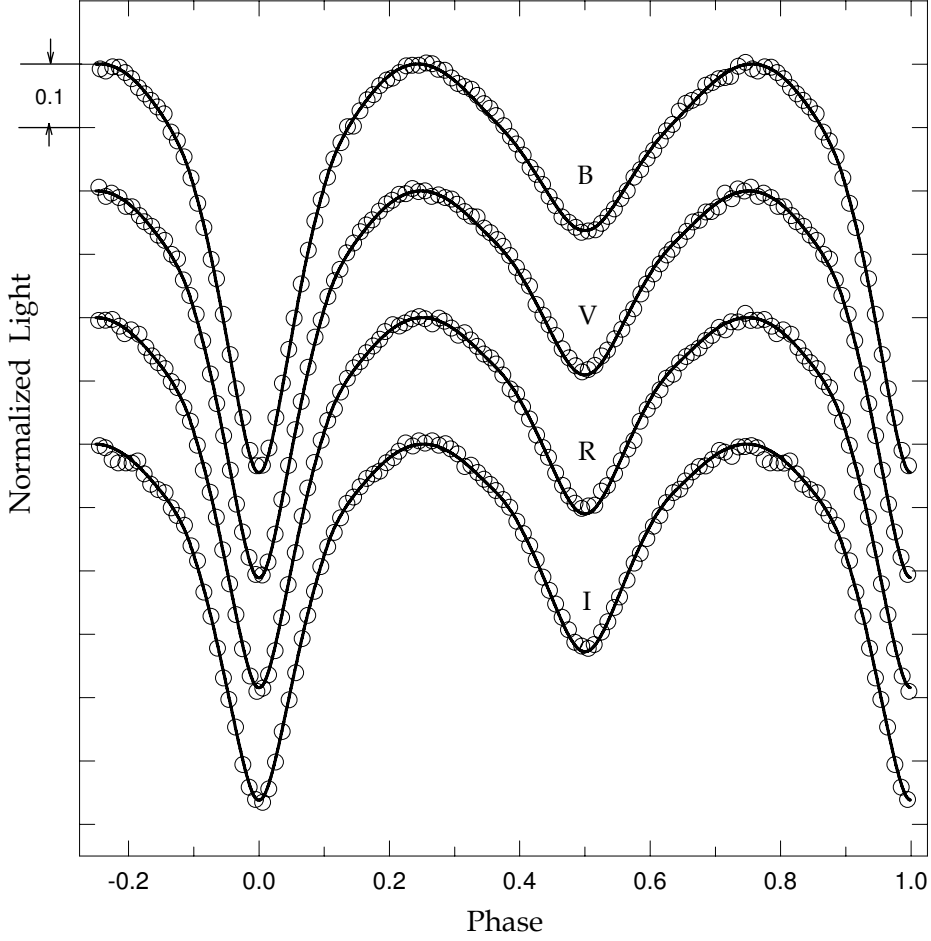


Fig. 2.— Normalized observations of WZ Cyg with the theoretical light curves obtained by fitting simultaneously all SOAO data. For clarity, individual measures have been compiled into 100 mean points using bin widths of 0.01 in phase for each filtered light curve. The continuous curves represent the solutions obtained with our model parameters listed in Table 2.

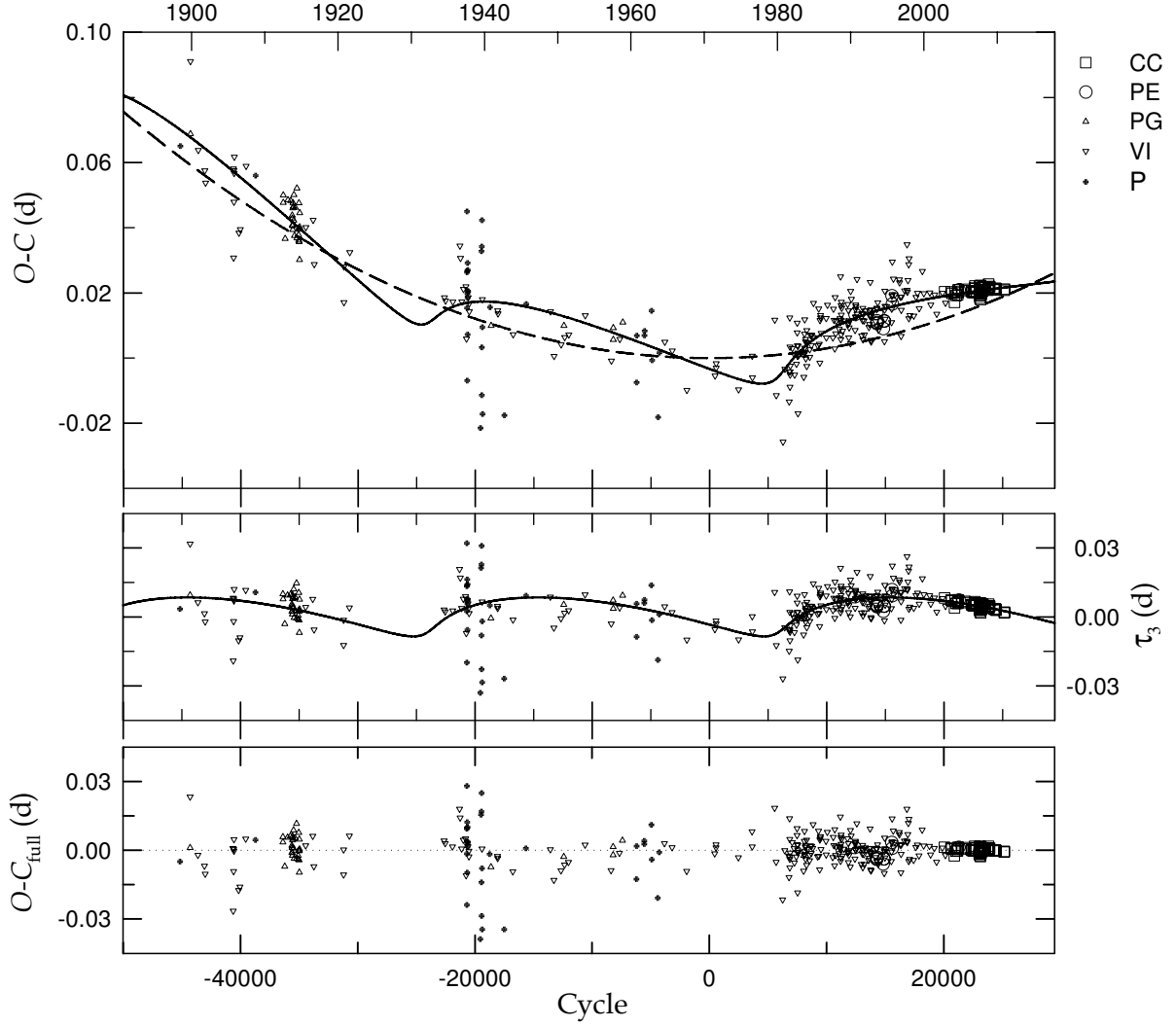


Fig. 3.— $O-C$ diagram of WZ Cyg constructed with the linear terms of the quadratic *plus* LTT ephemeris. In the top panel, the continuous curve and the dashed, parabolic one represent the full contribution and the quadratic term of the equation, respectively. The middle panel represents the LTT orbit and the bottom panel the residuals from the complete ephemeris. CC, PE, PG, VI, and P denote CCD, photoelectric, photographic, visual, and photographic plate minima, respectively.

Table 1. CCD photometric observations of WZ Cyg.

HJD	ΔB	HJD	ΔV	HJD	ΔR	HJD	ΔI
2,454,399.91834	−0.840	2,454,399.91963	−0.768	2,454,399.92078	−0.750	2454399.92184	−0.696
2,454,399.92314	−0.839	2,454,399.92446	−0.782	2,454,399.92560	−0.760	2454399.92666	−0.707
2,454,399.92795	−0.828	2,454,399.92927	−0.774	2,454,399.93042	−0.735	2454399.93149	−0.674
2,454,399.93282	−0.834	2,454,399.93417	−0.767	2,454,399.93531	−0.707	2454399.93639	−0.666
2,454,399.93773	−0.827	2,454,399.93907	−0.755	2,454,399.94022	−0.727	2454399.94129	−0.650
2,454,399.94262	−0.809	2,454,399.94397	−0.761	2,454,399.94513	−0.711	2454399.94620	−0.658
2,454,399.94753	−0.812	2,454,399.94888	−0.757	2,454,399.95002	−0.720	2454399.95109	−0.638
2,454,399.95242	−0.794	2,454,399.95377	−0.717	2,454,399.95492	−0.693	2454399.95599	−0.620
2,454,399.95732	−0.778	2,454,399.95867	−0.716	2,454,399.95981	−0.678	2454399.96090	−0.612
2,454,399.96223	−0.802	2,454,399.96357	−0.728	2,454,399.96472	−0.679	2454399.96579	−0.610

Note. — This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.

Table 2. Binary parameters of WZ Cyg.

Parameter	Siwak et al. (2010)		This paper	
	Primary	Secondary	Primary	Secondary
T_0 (HJD)			2,454,407.938339±0.000060	
P (d)			0.58446888±0.00000013	
q		0.631	0.6300±0.0011	
i (deg)		83.497	83.207±0.052	
T (K)	6530	4932	6530	5083±9
Ω	3.1200	3.1200	3.1005±0.0029	3.1005
Ω_{in}		3.1199	3.1182	
A	0.50	0.50	0.700±0.056	0.50
g	0.32	0.32	0.356±0.018	0.32
X, Y			0.639, 0.241	0.643, 0.169
x_B, y_B			0.804, 0.238	0.852, 0.001
x_V, y_V			0.709, 0.277	0.796, 0.131
x_R, y_R			0.615, 0.284	0.710, 0.185
x_I, y_I			0.524, 0.271	0.613, 0.201
$L/(L_1 + L_2)_B$	0.8691	0.1309	0.8852±0.0019	0.1148
$L/(L_1 + L_2)_V$	0.8453	0.1547	0.8381±0.0017	0.1619
$L/(L_1 + L_2)_R$	0.8233	0.1767	0.8034±0.0015	0.1966
$L/(L_1 + L_2)_I$	0.7854	0.2146	0.7737±0.0013	0.2263
r (pole)	0.3948	0.3183	0.3976±0.0005	0.3209±0.0005
r (side)	0.4174	0.3327	0.4210±0.0006	0.3359±0.0006
r (back)	0.4465	0.3649	0.4512±0.0007	0.3697±0.0010
r (volume) [†]	0.4210	0.3400	0.4250	0.3439

[†]Mean volume radius.

Table 3. Absolute parameters for WZ Cyg.

Parameter	Primary	Secondary
M (M_{\odot})	1.59 ± 0.04	1.00 ± 0.02
R (R_{\odot})	1.72 ± 0.02	1.39 ± 0.02
$\log g$ (cgs)	4.17 ± 0.02	4.15 ± 0.01
ρ (g cm^3)	0.44 ± 0.02	0.53 ± 0.02
T (K)	6530 ± 200	5083 ± 200
L (L_{\odot})	4.80 ± 0.60	1.15 ± 0.18
M_{bol} (mag)	$+3.03 \pm 0.14$	$+4.57 \pm 0.11$
BC (mag)	$+0.01$	-0.27
M_V (mag)	$+3.02 \pm 0.14$	$+4.84 \pm 0.11$

Table 4. Photoelectric and CCD timings of minimum light for WZ Cyg.

HJD (2,400,000+)	HJED (2,400,000+)	Error	Epoch	$O-C_{\text{full}}$	Min	References
48,073.4709	48,073.47156		12401.0	+0.00111	I	Hanzl(1991)
49,163.5002	49,163.50088		14266.0	−0.00396	I	Rovithis et al. (1996)
49,164.3800	49,164.38068		14267.5	−0.00086	II	Rovithis et al. (1996)
49,168.4685	49,168.46918		14274.5	−0.00364	II	Rovithis et al. (1996)
49,169.3457	49,169.34640		14276.0	−0.00312	I	Rovithis et al. (1996)
49,490.5083	49,490.50900		14825.5	−0.00605	II	Rovithis et al. (1996)
49,529.3778	49,529.37850		14892.0	−0.00372	I	Rovithis et al. (1996)
49,530.5466	49,530.54730		14894.0	−0.00386	I	Rovithis et al. (1996)
49,917.4720	49,917.47271	±0.00040	15556.0	+0.00335	I	Albayrak et al. (2000)
49,938.5103	49,938.51101	±0.00030	15592.0	+0.00078	I	Albayrak et al. (2000)
52,546.4087	52,546.40944	±0.00070	20054.0	+0.00132	I	Agerer & Hübscher (2003)
52,870.2037	52,870.20444	±0.00020	20608.0	+0.00092	I	Nagai (2004)
52,902.3490	52,902.34974	±0.00100	20663.0	+0.00047	I	Brát et al. (2007)
53,040.2806	53,040.28134	±0.00080	20899.0	−0.00243	I	Sobotka (2007)
53,116.2635	53,116.26424	±0.00020	21029.0	−0.00040	I	Nagai (2005)
53,193.4134	53,193.41414	±0.00130	21161.0	−0.00030	I	Brát et al. (2007)
53,202.7655	53,202.76624	±0.00050	21177.0	+0.00031	I	Sobotka (2007)
53,206.2728	53,206.27354	±0.00030	21183.0	+0.00080	I	Sobotka (2007)
53,224.3918	53,224.39254	±0.00180	21214.0	+0.00129	I	Brát et al. (2007)
53,259.4598	53,259.46054	±0.00130	21274.0	+0.00120	I	Hübscher et al. (2005)
53,546.4336	53,546.43434	±0.00180	21765.0	+0.00112	I	Brát et al. (2007)
53,612.4780	53,612.47874	±0.00380	21878.0	+0.00061	I	Hübscher et al. (2006)
53,887.1776	53,887.17835	±0.00020	22348.0	+0.00019	I	Nagai (2007)
53,920.4919	53,920.49265	±0.00010	22405.0	−0.00020	I	Hübscher (2007)
53,985.3679	53,985.36865	±0.00010	22516.0	−0.00016	I	Doğru et al. (2007)
54,003.4867	54,003.48745	±0.00010	22547.0	+0.00012	I	Hübscher (2007)
54,018.39034	54,018.39109	±0.00020	22572.5	−0.00017	II	Siwak et al. (2010)
54,019.26728	54,019.26803	±0.00010	22574.0	+0.00006	I	Siwak et al. (2010)
54,020.43612	54,020.43687	±0.00005	22576.0	−0.00003	I	Siwak et al. (2010)
54,279.64626	54,279.64701	±0.00063	23019.5	−0.00151	II	This paper (WASP)
54,282.57021	54,282.57096	±0.00036	23024.5	+0.00009	II	This paper (WASP)
54,284.61529	54,284.61604	±0.00026	23028.0	−0.00046	I	This paper (WASP)
54,286.66135	54,286.66210	±0.00040	23031.5	−0.00004	II	This paper (WASP)
54,287.53895	54,287.53970	±0.00027	23033.0	+0.00086	I	This paper (WASP)
54,288.70734	54,288.70809	±0.00026	23035.0	+0.00031	I	This paper (WASP)
54,289.58525	54,289.58600	±0.00038	23036.5	+0.00152	II	This paper (WASP)

Table 4—Continued

HJD (2,400,000+)	HJED (2,400,000+)	Error	Epoch	$O-C_{\text{full}}$	Min	References
54,291.62883	54291.62958	± 0.00016	23040.0	-0.00054	I	This paper (WASP)
54,292.50708	54292.50783	± 0.00035	23041.5	$+0.00101$	II	This paper (WASP)
54,298.64267	54298.64342	± 0.00010	23052.0	-0.00032	I	This paper (WASP)
54,304.48665	54304.48740	± 0.00024	23062.0	-0.00102	I	This paper (WASP)
54,306.53106	54306.53181	± 0.00067	23065.5	-0.00225	II	This paper (WASP)
54,308.57840	54308.57915	± 0.00024	23069.0	-0.00055	I	This paper (WASP)
54,326.1127	54326.11345	± 0.00010	23099.0	-0.00029	I	Nagai (2008)
54,333.42045	54333.42120	± 0.00017	23111.5	$+0.00161$	II	This paper (WASP)
54,335.46381	54335.46456	± 0.00015	23115.0	-0.00067	I	This paper (WASP)
54,337.51039	54337.51114	± 0.00040	23118.5	$+0.00027$	II	This paper (WASP)
54,338.38632	54338.38707	± 0.00021	23120.0	-0.00050	I	This paper (WASP)
54,339.55539	54339.55614	± 0.00020	23122.0	-0.00037	I	This paper (WASP)
54,340.42969	54340.43044	± 0.00049	23123.5	-0.00277	II	This paper (WASP)
54,344.52371	54344.52446	± 0.00047	23130.5	-0.00003	II	This paper (WASP)
54,346.56912	54346.56987	± 0.00021	23134.0	-0.00026	I	This paper (WASP)
54,364.39486	54364.39561	± 0.00044	23164.5	-0.00079	II	This paper (WASP)
54,371.40781	54371.40856	± 0.00042	23176.5	-0.00146	II	This paper (WASP)
54,373.45455	54373.45530	± 0.00021	23180.0	-0.00036	I	This paper (WASP)
54,395.37267	54395.37342	± 0.00048	23217.5	$+0.00020$	II	This paper (WASP)
54,397.41793	54397.41868	± 0.00022	23221.0	-0.00017	I	This paper (WASP)
54,400.04833	54,400.04908	± 0.00059	23225.5	$+0.00012$	II	This paper (SOAO)
54,407.93824	54,407.93899	± 0.00028	23239.0	-0.00029	I	This paper (SOAO)
54,426.05679	54,426.05754	± 0.00024	23270.0	-0.00025	I	This paper (SOAO)
54,433.3627	54,433.36345	± 0.00030	23282.5	-0.00019	II	Brát et al. (2008)
54,455.2815	54,455.28225	± 0.00010	23320.0	$+0.00105$	I	Hübscher et al. (2009)
54,712.15401	54,712.15476	± 0.00020	23759.5	-0.00018	II	This paper (SOAO)
54,716.24572	54,716.24647	± 0.00033	23766.5	$+0.00025$	II	This paper (SOAO)
54,741.96376	54,741.96451	± 0.00038	23810.5	$+0.00170$	II	This paper (SOAO)
54,748.97644	54,748.97719	± 0.00043	23822.5	$+0.00076$	II	This paper (SOAO)
54,751.02142	54,751.02217	± 0.00013	23826.0	$+0.00010$	I	This paper (SOAO)
54,753.94393	54,753.94468	± 0.00008	23831.0	$+0.00027$	I	This paper (SOAO)
54,755.11277	54,755.11352	± 0.00008	23833.0	$+0.00017$	I	This paper (SOAO)
54,760.08100	54,760.08175	± 0.00020	23841.5	$+0.00042$	II	This paper (SOAO)
54,798.3641	54,798.36485	± 0.00010	23907.0	$+0.00086$	I	Hübscher et al. (2009)
55,018.1231	55,018.12387	± 0.00010	24283.0	-0.00013	I	Nagai (2009)
55,079.4924	55,079.49317	± 0.00030	24388.0	$+0.00002$	I	Erkan et al. (2010)
55,091.18180	55,091.18257	± 0.00007	24408.0	$+0.00006$	I	This paper (SOAO)

Table 4—Continued

HJD (2,400,000+)	HJED (2,400,000+)	Error	Epoch	$O-C_{\text{full}}$	Min	References
55,115.14457	55,115.14534	± 0.00020	24449.0	-0.00036	I	This paper (SOAO)
55,526.02520	55,526.02597	± 0.00013	25152.0	-0.00081	I	This paper (SOAO)
55,528.94785	55,528.94862	± 0.00015	25157.0	-0.00050	I	This paper (SOAO)

Table 5. Parameters for the quadratic *plus* LTT ephemeris of WZ Cyg.

Parameter	Values	Unit
T_0	$2,440,825.47487 \pm 0.00061$	HJED
P	$0.584467647 \pm 0.000000027$	d
A	$+(3.02 \pm 0.11) \times 10^{-11}$	d
$a_{12} \sin i_3$	1.72 ± 0.21	AU
ω	320.0 ± 4.1	deg
e	0.67 ± 0.19	
n	0.02058 ± 0.00078	deg d $^{-1}$
T	$2,444,328 \pm 379$	HJED
P_3	47.9 ± 1.8	yr
K	0.0085 ± 0.0011	d
$f(M_3)$	0.00220 ± 0.00029	M_{\odot}
M_3 ($i_3=90$ deg) †	0.26	M_{\odot}
M_3 ($i_3=60$ deg) †	0.31	M_{\odot}
M_3 ($i_3=30$ deg) †	0.56	M_{\odot}
dP/dt	$+(3.78 \pm 0.14) \times 10^{-8}$	d yr $^{-1}$
dM_2/dt	-5.80×10^{-8}	M_{\odot} yr $^{-1}$

† Hypothetical third-body masses for different values of i_3 .

Table 6. Applegate parameters for possible magnetic activity of WZ Cyg.

Parameter	Primary	Secondary	Unit
ΔP	0.1523	0.1523	s
$\Delta P/P$	3.02×10^{-6}	3.02×10^{-6}	
ΔQ	8.38×10^{49}	5.27×10^{49}	g cm^2
ΔJ	2.49×10^{47}	1.86×10^{47}	$\text{g cm}^2 \text{ s}^{-1}$
I_s	3.02×10^{54}	1.24×10^{54}	g cm^2
$\Delta \Omega$	8.22×10^{-8}	1.50×10^{-7}	s^{-1}
$\Delta \Omega/\Omega$	6.61×10^{-4}	1.21×10^{-3}	
ΔE	4.09×10^{40}	5.59×10^{40}	erg
ΔL_{rms}	8.50×10^{31}	1.16×10^{32}	erg s^{-1}
	0.0218	0.0298	L_{\odot}
	0.0045	0.0259	$L_{1,2}$
Δm_{rms}	± 0.0040	± 0.0054	mag
B	4,350	5,183	G